Historical Development of Arch Dams: from cut-stone arches to modern concrete designs *

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SUMMARY: *Dam designs may be divided into three main types : gravity structures relying on their weight for stability, arch structures using the abutment reaction forces and buttress dams. The design of an arch dam relies on the abutment reaction forces to resist the water pressure force and it requires advanced engineering expertise. The present study demonstrates that the historical development of arch dams took place in five stages. The world's oldest arch dams were built by the Romans in France and Spain. They were followed by the Mongols who built dams in Iran during the 13th and 14th centuries. However it is not until the 19th century that significant progress in arch dam design was made. Four remarkable structures were the Meer Allum dam (India 1804), the Jones Falls dam (Canada 1831), the Zola dam (France 1854) and Parramatta dam (Australia 1856). Australian engineers pioneered the use of concrete as a construction material for arch dams (ie. 75-Miles and Lithgow No. 1 dams). Modern concrete arch dam designs were introduced in North America at the beginning of the 20th century: eg. constant-angle arch, double-curvature arch. Since then no major design breakthrough has taken place and modern arch dams are based upon the single-radius, constant-angle or double-curvature arch design. It is the writers' opinion that the introduction of concrete as construction material marked a major innovation in allowing a flexibility in arch shape design.*

NOTATION

- E dam base thickness (m);
- e dam crest thickness (m);
- H dam height above foundation (m);
- L arch dam crest length (m)
- R radius of curvature (m) of arch wall;
- θ arch opening angle;

1 INTRODUCTION

Dam designs may be divided into three main types : gravity structures relying on their weight for stability, arched structures using the abutment reaction forces and buttress dams. Historically, the first dams were earthfill and rockfill embankments, eg. Sadd-El-Kaffara (Egypt BC 2800-2600), Marib (Yemen BC 750), Panda Wewa (Sri Lanka BC 400-300), Cornalvo (Spain AD 150-200), see figure 1. Concrete and stone masonry dams, commonly called gravity dams, were built at sites where good quality stones were available, eg. Khosr River (Irak BC 694), Al-Harbaqa (Syria AD 132), Kasserine (Tunisia AD 100-200). Sometimes, the dam wall was reinforced by masonry buttresses, eg.Alcantarilla (Spain BC 200-100), Proserpina (Spain AD 130).Later designs included arch dams, relying on the abutment reaction forces to resist the resulting water pressure force. A related design is the multiple-arch buttress dam, consisting of a series of arches supported by buttresses.

Smith[1] and Schnitter[2] presented comprehensive treatises on the history of dams. However, arch dam design was rare up to the late 19th century and the historical development of such dams received less attention, with one notable exception.[3]

The present work will show that the historical development of arch dams progressed during five periods: the Roman arch dams (1st centuries BC and AD), the Mongol dams (14 and 15th centuries), some advanced masonry dams in the early 19th century (1804-1856), the Australian concrete arch dams (1880-1896) and the modern arch shapes at the beginning of the 20th century (1903-1928).

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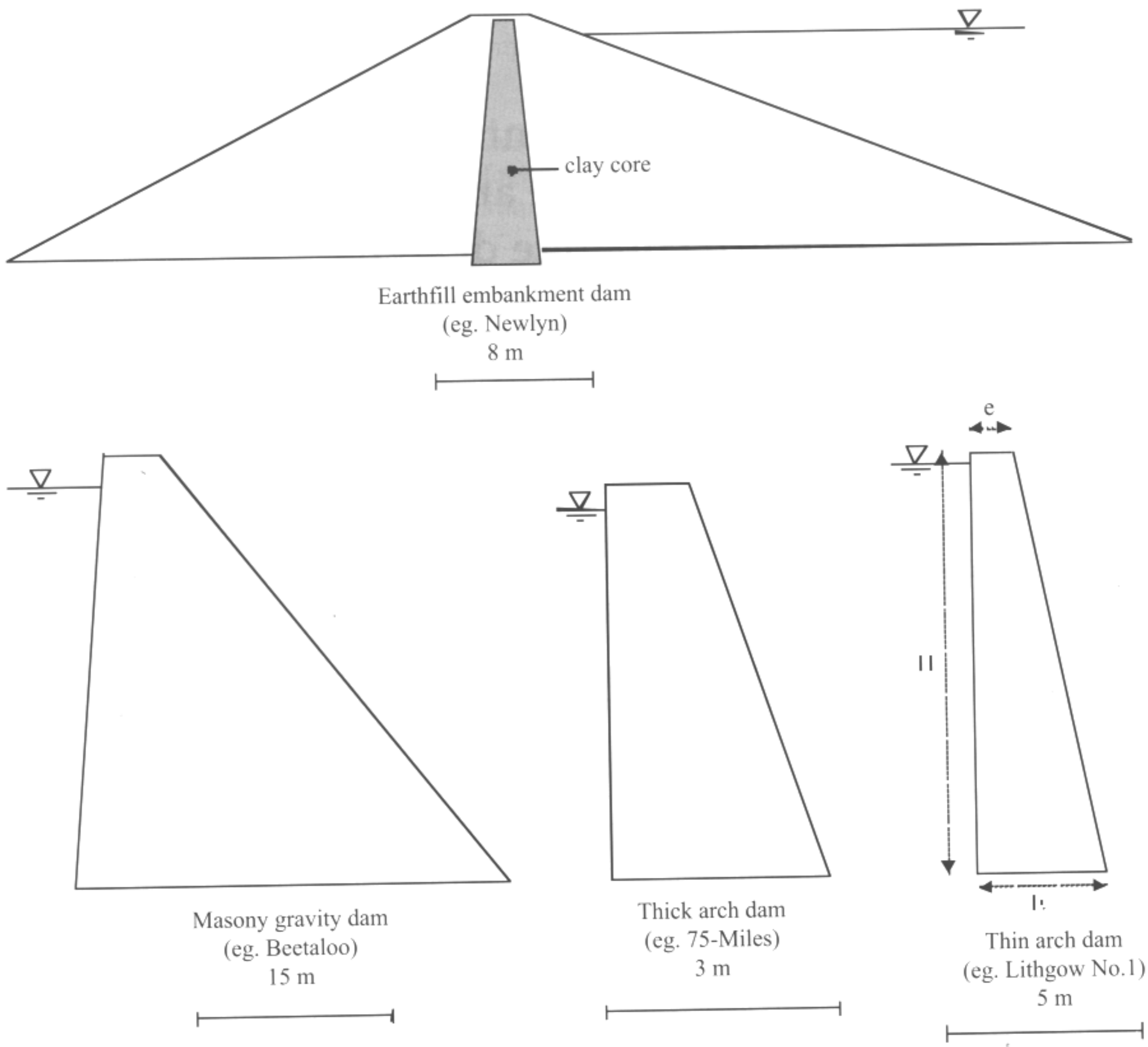


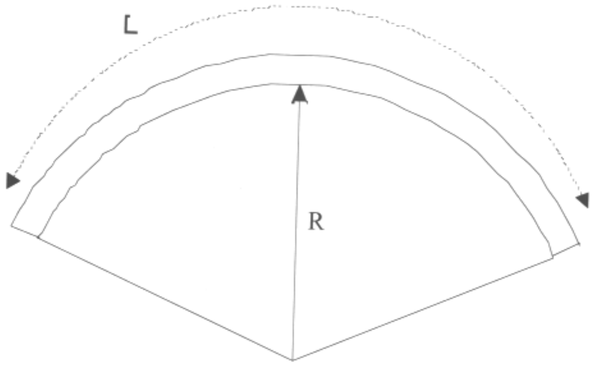
Figure 1: Typical cross-sectional shapes of gravity and arch dams

Terminology

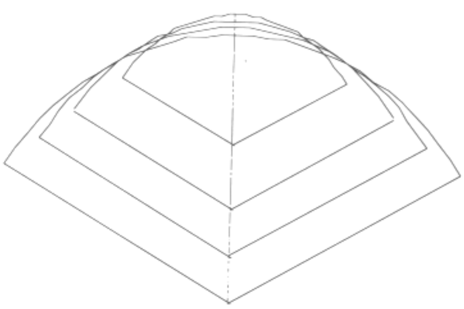
It is inadequate to define a dam as curved or arched because it does not identify the relative importance of the gravity and the abutment forces in providing stability. Such a dam should correctly be called a curved gravity, thick-arch or thin-arch structure. A *curved gravity dam* is primarily a gravity structure relying on its weight for its stability and the wall curvature adds little to its stability. By contrast, an *arch dam* would be unstable without the contribution of the abutment reaction forces. A *thick-arch dam* relies both on its weight and on the abutment reaction for its stability. A *thin-arch dam* is a leaner structure relying predominantly on the abutment reaction forces for its stability; typically the ratio of the base thickness to the dam height (E/H) is less than one third.

Practically, the arch dam design is well adapted to narrow gorges and it produces substantial savings in costs compared to a gravity dam. In figure 1, typical cross-sections of gravity and arch dams are compared.

The basic arch dam shapes are the constant-radius arch, the constant-angle arch and the double-curvature arch with increasing complexity. The *constant-radius arch* design, also called the single-radius arch, is a cylindrical shape (figure 2). The upstream face is usually vertical while the downstream face is battered. The *constant-angle arch* design is a variable-radius arch. The design is based on a constant central opening angle, with the arch radius increasing from base to crest; a concept first introduced by Albert G Pelletreau(1843-1900) in 1879.[4] It results in considerable saving in construction material, compared to the constant-radius arch design. Lars R Jorgensen (1876-1938), who applied the concept, demonstrated that the dam contained minimum material for an optimum opening angle of 133.6 degrees.[5] He added, however, that "the use of a smaller central angle [...] might be more economical, and 120 degrees or even less [...] might give very satisfactory results".The *double-curvature arch* design, also called spherical dome or cupola, has a more complex shape and vertical curvature is introduced. The shell design results in saving in concrete but requires more technical skills that for a constant-angle arch dam.



Cylindrical arch



Constant-angle (variable-radius) arch

Figure 2: Comparative plan-view sketch of single-radius and constant-angle arch dams

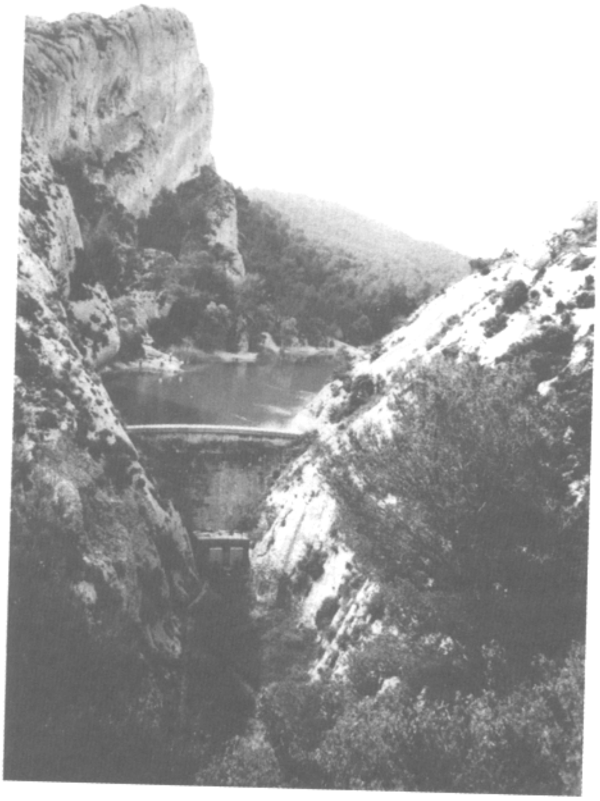


Figure 3: Les Peirou dam at Saint-Rémy-de-Provence, France
Thick arch dam built on the Roman dam foundations, in 1891 (H = 19 m, e = 1 m, E = 7 m, L = 22.4 m, storage capacity : 8 E+4 m[3])

2 ROMAN ARCH DAMS

The first arch dam is probably the Roman dam at Glanum, built during the first century BC to supply water to the Roman town (table 1). It is also called Les Peirou dam. A newer dam was built in 1891 at the same place, above the Roman dam foundation (figure 3). Today, the site of Glanum is located 1 km South of the town of Saint-Rémy-de-Provence, France. The Roman dam was rediscovered in 1763 by Esprit Calvet.[6,7] A recent study[8] indicated that the dam was made of cut stones held together with crampons and finished with waterproof cordon joints. The site was well selected (figure. 3) and the wall abutments were cut in the rock.

Another unusual Roman dam was the Esparragalejo dam, near Merida (table 1). Built around the 1st century AD for irrigation purposes, the structure was a multiple-arch buttress dam, 5.6 m high and 2 m thick at base with circular arches.

Discussion

The Romans built gravity embankment dams, eg. Alcantarilla, Spain BC 200-100; Proserpina, Spain AD 130; straight masonry gravity dams, eg. Al-Harbaqua, Syria AD 132; and curved-gravity dams, eg. Kasserine dam, Tunisia, AD 100?[9], Çavdarhisar dam, Turkey.[2] But the dam at Glanum was unique. It was a slender thin arch dam (E/H = 0.265). The writers hypothesise that the arch dam design was introduced because the site was favourable to a masonry dam (figure 3) but nearby construction materials were scarce.

The arch technique was applied by the Romans to sewers, aqueducts and bridges, although there is no evidence of scientific design rules. Professor C O'Connor suggested that, for Roman bridges, the ratio of arch rib thickness to span was about 1/10 for spans less than 15 m and could be reduced down to 1/20 for greater spans.[10] Interestingly the ratio of dam wall thickness to arch curvature radius was between 1/10 and 1/7 at Glanum: ie. close to Roman bridge dimensions.

For completeness, some researchers suggested the existence of further Roman arch dams, eg. Kasserine (Tunisia), Dara (Turkey), Çavdarhisar (Kütahya, Turkey), Örükaya (Çorum, Turkey). The Çavdarhisar and Örükaya dams were flood retention structures. Their scour outlet system had cross-section areas of 11 m and 3 m^2 respectively. A re-analysis of these structures demonstrated that Kasserine, Çavdarhisar and Örükaya were curved gravity dams. In the particular case of Dara, the Byzantine historian Procopius (6th century AD) indicated a curved dam, possibly as at Kasserine, and no remains are visible.

3 MONGOL ARCH DAMS

During the 13th century, the Mongols invaded and settled in Iran where they built several large dams, eg. the Saveh dam was a gravity dam built in AD 1285 (H = 25 m, L = 65 m). Around the 14th century, they built also some arch dams (table 1). The Mongol arch dams in Iran had thick arch walls and they were significantly higher than the Roman dams. The first arch dam (Kebar, AD 1300) was heightened to 26 m around AD 1600 while the Kurit dam was 60 m high before heightening.[13,14] The Kurit dam was extraordinary, having the very-low crest length to dam height ratio L/H of 0.42 after heightening (probably less prior). It is interesting to note that these structures were used for several centuries. Several dams were still standing in the 1970s although some were subjected to foundation failures, eg. Chabb Abbasi. The complete upper portion of the dam wall was still standing in the 1970s despite the missing foundation.[14] In the authors' opinion, this highlights the soundness of the arch wall design and the quality of the masonry work. The Mongol dams were further equipped with sophisticated outlet systems (eg. Kebar, Kurit).

Discussion

Some transfer of expertise on arch dam design might have taken place from the Romans to the Iranians. After the defeat of Valerian's army (Roman emperor from AD 253 to 260) in AD 260, 70,000 men were captured and transported to Persia where they were forced to work. The Roman army was often involved in large-scale civil engineering works, in particular aqueduct constructions, and it is likely that it was also involved in dam construction. The Roman prisoners built bridge-weirs and dams in Iran. Examples of bridge-weir include Dezful and Shustar, and an example of dam is Ahwaz. Shustar dam is also called Band-i-Kaisar or "Dam-Bridge of Valerian".[10] Ahwaz dam, also called Ahvaz weir, was a 900 m long masonry weir on Karun river.

Some structures, for example Shustar bridge-weir, were still in use when the Mongols invaded in Iran. There is however no proof that the Mongols were aware of the Roman arch dams.

The Roman and Mongol dams in Iran were milestones in arch dam development. From the 14th century up to the beginning of the 19th century, the arch dam development was scattered and disparate. An arch dam was built in Italy at Pontalto in 1612 and the structure was heightened more than six times over the next 270 years from 5 m to 37.8 m. In Spain, Don Pedro Bernardo Villareal de Berriz (1670-1740), a Basque nobleman, designed and built one single-arch and four multiple-arch dams with vertical circular arches in the 1730s. They were low-head structures used for water power purposes and four of them are still in good condition.

4 MASONRY ARCH DAMS IN THE EARLY 19TH CENTURY

During the first part of the 19th century, the arch dam design was dominated by four large structures. These were the Meer Allum (India), Jones Falls (Canada), Zola (France) and Parramatta (Australia) dams (table 1).

In India, Henry Russle, Royal Engineers, built [1] the extra-ordinary Meer Allum (Mir Alam) dam with a 10 Mm^3 water storage capacity around 1804. The multiple-arch dam was built to supply water to Hyderabad and it is still in use. It consists of 21 semi-circular vertical arches with span ranging from 21.3 to 44.8 m.

In Canada, John By, Lieutenant-Colonel, Royal Engineers, (1779-1836) (See Appendix I.) built several curved masonry dams between 1827 and 1832 as part of the Rideau waterway system. One, the Jones Falls dam, was a true arch dam. Completed in 1831, the 18.7 m high dam was a constant-radius arch wall, 8.4 m thick at base (table 1). The dam is still used today for hydropower and navigation purposes.

François Zola (1795-1847)(father of the French novelist Emile Zola, 1840-1902) designed two arch dams in 1832 for the water supply of Aix-en-Provence, France. One, the Zola dam, was built between 1847 and 1854. It was the first arch dam design based on a rational stress analysis. The reservoir was used as a town water supply until 1877. Today it is still in use for flood retention, (figure 4).

One of the first significant hydraulic structures in Australia was the Parramatta dam near Sydney (figure 5, table 1). Built between 1851 and 1856, the 12.5 m high arch dam was designed by P Simpson (1789-1877), EO Moriarty (1824-1896) and W Randle.[20] It was a constant-radius arch with a cylinder shape and it was heightened by 3.35 m in 1898 under the supervision of Cecil West Darley (1842-1928).[21]

Figure 4: Zola dam, Aix-en-Provence, France in June 1998
H = 24.5 m, L = 66 m, E = 13 m, e =5 m, R = 48.2, θ = 77° (1854)

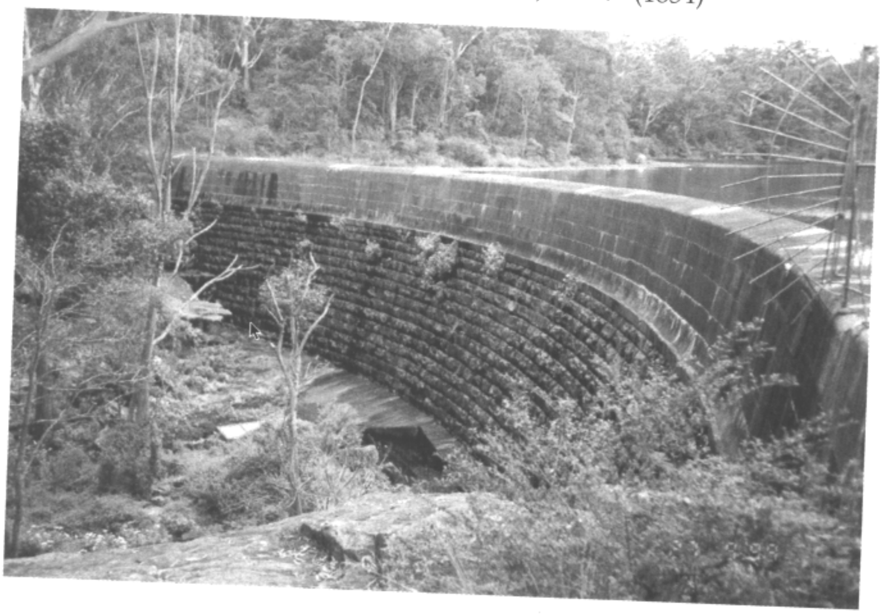


Figure 5: Parramatta dam, Sydney, Australia on 27 September 1999
H = 12.5 / 15.8 m, L = 80 m, E = 4.6 m, e = 2.3 / 1.46 m, R = 48.8 (1856 / 1898)

Discussion

All four structures were constant-radius arches built in cut-stone masonry. It is generally believed that the thickness of the cylindrical arch was calculated using the thin cylinder formula because the concept was familiar at the time to engineers involved in shell and ship hull calculations. For example, two of the designers of the Parramatta dam, namely Simpson and Moriarty, were respectively a former officer of the Royal Navy and a naval engineer, both of them familiar with the calculations of ship hulls.[20,22]

It is worth noting that three dams were built in the British empire. Two structures were designed by Royal Engineers : the Meer Allum multiple arch dam (1804?) and Jones Falls thick arch dam (1831). It is possible that these designs influenced the Australian engineers with a transfer of expertise taking place through Royal Engineers. The Royal Engineers in India had a strong involvement in water supply systems and they were sometimes called upon in Australia. The writers believe that the Royal Engineers in India were aware of the successes of Meer Allum and Jones Falls dams. Indeed the designer of Jones Falls dam, John By, was well-known and respected among the Royal Engineers and they might have advised Australian engineers.[2]

The four masonry arch dams are still in use for water supply (Meer Allum), hydropower (Jones Falls), flood retention (Zola) and recreation (Parramatta). Their long-lasting operation demonstrates the soundness of design and the quality of the masonry construction.

5 CONCRETE ARCH DAMS IN AUSTRALIA

Built near Warwick (Queensland), the 75-Miles dam was built to provide a water supply for steam locomotives.[25] The first dam was designed by Henry Charles Stanley (1840-1921). It was a concrete arch, 5.04 m high, 1.07 m thick at crest and 2.784 m at the base. The dam was equipped with an overflow spillway, a scour outlet and a water outlet feeding a water tank located below beside the railway line. In 1900-1901, the dam was heightened from 8 to 10 m under the supervision of Stanley. The enlargement included the addition of three concrete buttresses (figure 6). The 75-Miles dam built in 1880 was the oldest concrete arch dam built in Australia, and possibly the world's oldest concrete arch dam.[26] It was the second arch dam completed in Australia as well as the second dam built entirely of concrete in Australia. (The first concrete dam was the Lower Stony Creek dam near Geelong VIC completed in 1873.[27,28])

Completed in 1896, Lithgow No. 1 dam in New South Wales was built as a town water supply (figure 7). It was designed by CW Darley. The 10.7 m high dam was a concrete single-radius thin-arch structure , with a vertical upstream face and battered downstream face (1H:3.6V). It was equipped with an overflow section and an outlet system. In 1914 or 1915, the dam was heightened by closing the spillway overflow section and adding new wing walls. A new overfall spillway was built. The dam became disused around 1983-84 because the reservoir did not have enough available head to feed the new wastewater treatment plant. It has been kept empty since 1986 and it is now used as a flood retention reservoir (figure 7). Lithgow No. 1 dam was the first Australian thin-arch dam, and it is the world's oldest concrete thin-arch structure.[25] The design by Darley became a standard, commonly called 'Darley-Wade dam' design in Australia.[25]

Between 1907 and 1909, Ernest Macartney de Burgh (1863-1929) built two thin-arch dams in New South Wales, de Burgh Dam (1907-08) and Barren Jack City Dam, also called Barren Jack Creek dam, (1908-09). This was as part of the construction of the Burrinjuck reservoir, also called Burrenjick or Barren Jack dam,Barren Jack NSW, 1927 (concrete gravity structure, H = 61 m, L = 233 m).[25] The first-completed, de Burgh Dam, was built to supply water to the railway supplying the Burrinjuck dam construction site. The railway was a narrow-gauge railway for cement supply and operated from June 1908 to April 1929. The transport of cement (50,000 tonnes) was a critical factor in the construction of the Burrinjuck dam given the remote location of the site. It was a reinforced-concrete, single-radius, thin-arch dam (figure 8). The concrete wall was reinforced with 20 lb rails, 1.52 m apart horizontally and 3.048 m apart vertically.[3] De Burgh dam was a true reinforced-concrete arch with rail reinforcement placed from toe to crest. The wall reinforcement was not a standard design feature of the Darley-Wade dams. With Hume Lake dam (see below), de Burgh dam is the world's oldest reinforced-concrete thin arch dam.[25]

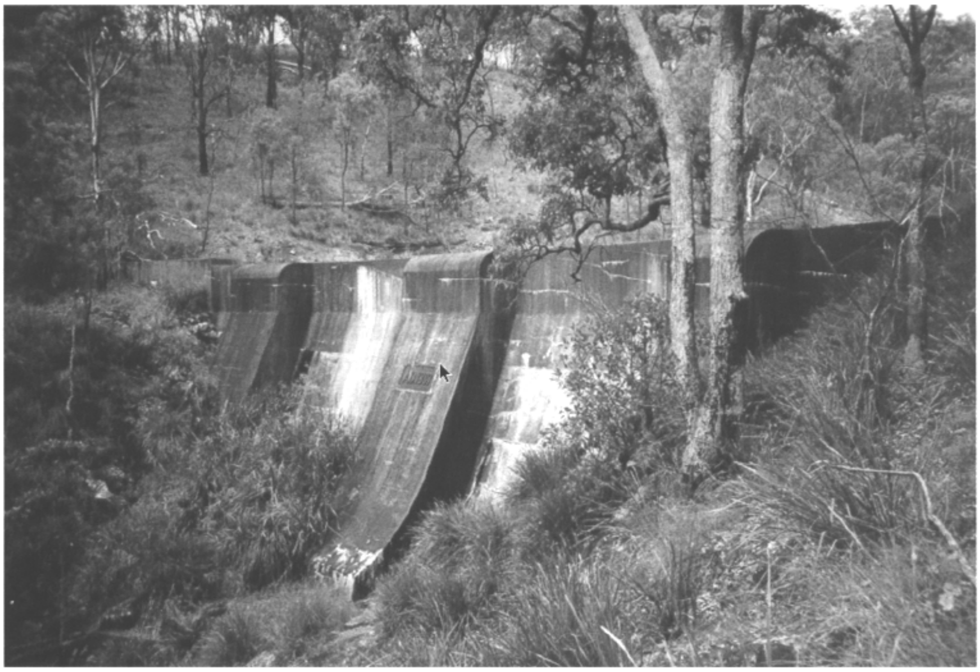


Figure 6a: 75-Miles dam (Warwick QLD, Australia)
H = 5.04 / 8 m, L = 24.5 / 30 m, E = 2.78 m, e = 1.07 / 0.89 m, R = 58.5, $\theta = 24^{\circ}$ (1880 / 1901)
View from downstream of the dam with the three concrete buttresses (Photograph taken on 23 January 1998)

Figure 6b: 75-Miles dam (Warwick QLD, Australia). Details of the dam crest and buttresses. Photograph taken 23 January 1998.

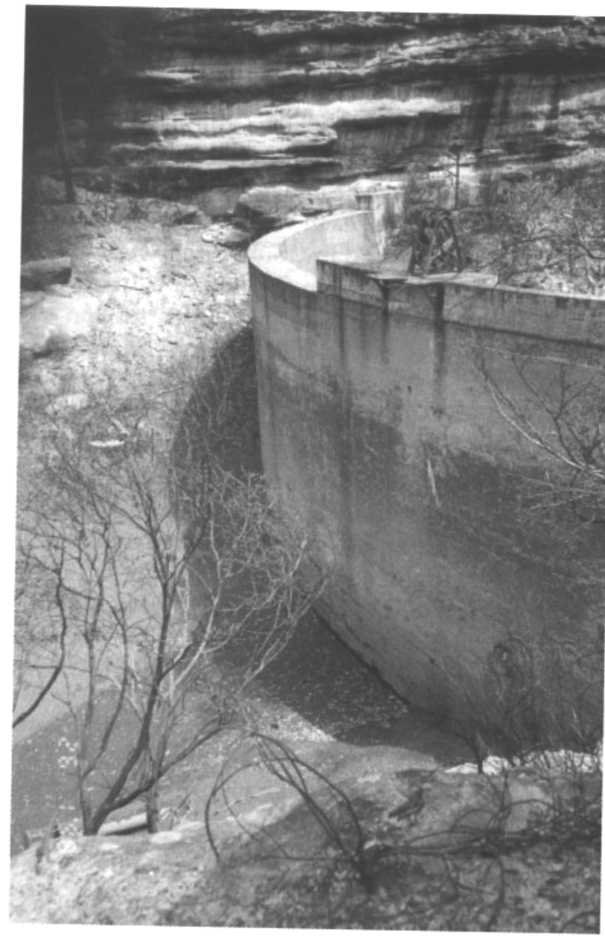


Figure 7: Lithgow No. 1 dam (Lithgow NSW, Australia) (Photograph taken on 26 January 1998)
H = 10.7 m, L = 54.3 m, E = 3.3 m, e = 1.07 m, R = 30.5 m, θ= 102° (1896)
View from upstream and right bank

Figure 8: De Burgh dam (Barren Jack NSW, 1908) (Photograph taken in July 1998)
H = 4.9 m, L = 30.2 m, e = 0.4 m, R = 20.2 m (1908)
View from right bank during a flood

The oldest multiple arch dam in Australia

Completed near Lyndhurst (NSW) in 1897, Junction Reefs dam (also called Junction Point Reefs dam or Belubula dam [2,29]) is a multiple-arch dam, 18.3 m high (figure 9). It was designed by O Schulze. There are 5 elliptical arches, each with a 8.5 m span and a 60 degrees lean. The dam foundation and outside walls were made of concrete while the arches and buttresses were built in brick. Brick construction was selected as the cheapest and quickest material to build for the arches as there was presence of good clay for brick-making near the dam site and concrete was cheaper only for the foundation.[29] Curiously the original design included six arches but the final design had only five arches because of delays in the brick-making. The arches were designed in the same way as bridge arches.[5] Built to provide hydropower for the nearby gold mine, the dam suffered heavy siltation and the reservoir is fully silted today. The design of Junction Reefs has been well-known overseas.[1,2,30]

6 MODERN ARCH DAM DESIGNS

The introduction of concrete as a construction material for arch dams marked a significant advance. Designers were able to consider complex curved shapes to minimise the volume of construction material and the overall cost. The initial developments took place in North America (table 1).

Professor GS Williams (1866-1931) designed the world's oldest cupola dam (figure 10). The Ithaca dam (New York, USA, 1903) was designed to be a 27 m high structure, but construction was stopped when the dam height reached 9 m because of local community opposition.[24,30] An interesting construction detail was the brick facing used as concrete formwork.

The first concrete multiple arch dam was designed by John S Eastwood (1857-1924). The Hume Lake dam (California, USA 1908) was built in the Sierra Nevada Mountains in 114 days![30] The 206 m long 18.6 m high structure consisted of 12 circular arches (15.24 m span) inclined at 58 degrees with the horizontal and vertical in the upper 4.88 m section. The concrete reinforcement included old logging cables (over 12 km) and railroad scrap iron.The rapid constructio time was a record. The high altitutde location of the dam was of difficult access and a rapid construction led to a competitive cost.[2, 30]

Lars R Jorgensen is regarded as having designed the first constant-angle arch dam (table 1) although this may not be strictly correct: Jorgensen[5] mentioned a smaller constant-angle dam designed by an American HF Cameron in the Philippines around 1913-14. The 30 m high dam was used for Manilla's water supply. Completed in 1914, the Salmon Creek dam was 51.2 m high and the opening angle was 113 degrees. The arch radius ranged from 44.96 m at base to 100.9 m at crest.

Figure 9: Junction Reefs dam (Lyndhurst NSW, Australia) (Photograph taken on 28 December 1997)
H = 18.3 m, L = 131.4 m, E = 1.22 m (arch), e = 0.5 m (arch), R = 8.53 m (arch) (1897)
View from the left bank

Another advanced design was the Coolidge dam (Globe, Arizona, USA 1928). It was the first cupola-shaped multiple-arch structure. Consisting of three arches, it was designed and constructed by the US Bureau of Indian Affairs, and it is still in use for irrigation and hydropower.

Discussion

Although dams were built as early as BC 3,000, and concrete was used by the Romans, the world's first concrete dams were completed in 1872: Boyds Corner, New York, USA, built between 1866 and 1872[6] and Pérolles dam, Switzerland, (also called La Maigrauge dam) built from 1869 to 1872 and heightened in 1909. They were followed by others: eg. Lower Stony Creek,Australia, 1873; San Mateo (also called Lower Crystal Springs dam), San Mateo, California, USA, 1888. These were all gravity dams. In the United Kingdom, the first mass concrete gravity dam exceeding 15 m in height was the Abbeystead dam completed in 1881.[31] In Hong Kong, the Tytam dam, completed in 1887, was a concrete gravity structure with masonry stone facing. The Sand River gravity dam, completed in 1906, was the first concrete dam in South Africa.[24,30] The first arch dam was completed near Johannesburg in 1898 for mining purposes. In India, the first large concrete structure was the Periar (or Periyar) dam built between 1888 and 1897 near Madras.[24] In summary, the construction of concrete dams began in the 1870s and intensified at the turn of the century.[7]

Historically, after the Roman and Mongol era, the arch design fell out of favour until the 19th century. The development of arch dams was later facilitated by the introduction of concrete as a construction material. The world's oldest concrete thick arch and thin-arch dams were single-radius arches and were unreinforced: the designs were based on the thin cylinder formula.[21,32] The Australian concrete arch dam designs were acknowledged in Europe and in the USA.[1,2,21,24,30] Wegmann (in the discussion of Wade 1909)[21] stated that, in his opinion, "the curved dams built [...] in New South Wales had been designed more logically" than any other arch dams or curved-gravity dams.

Masonry construction: cut-stone or concrete

The zenith of stone masonry dam construction was the 1850-1900 period and the construction techniques were well documented.[33,34] Why then did the Australian engineers select concrete as a dam construction material? In Australia, concrete was used for waterworks, weirs and dams as early as the 1870s. By world standards, large and innovative concrete works were produced such as the great dome of the Melbourne Public Library. It was the world's largest reinforced concrete dome at the time (1908-13).[27] Concrete construction for arch dams was selected because of the lower cost, the facility of construction by unskilled labour and the ease for building irregular shapes compared to stone masonry construction.

Concrete was reportedly the cheapest construction material at the end of the century. Darley (1900) estimated the unit volume cost of Australian arch dams at \$8 per m^3 of masonry. (Cost in US\$ of the time, with an exchange rate of about £1 = US\$ 4.9.[24]) Table 2 shows that the unit cost of concrete dam construction dropped from the 1870s to the 1900s to become lower than that of stone masonry. Darley's choice was consistent, although in advance, with that of world-known dam engineers.[8] Interestingly, brick was selected at Junction Reefs dam (1897) as being cheaper than concrete at this particular site.

Another advantage of concrete over cut-stone was the comparative ease of construction by labourers and horse-drawn carts. At Lower Stony Creek, "owing chiefly to the scarcity of masons, [...] the dam

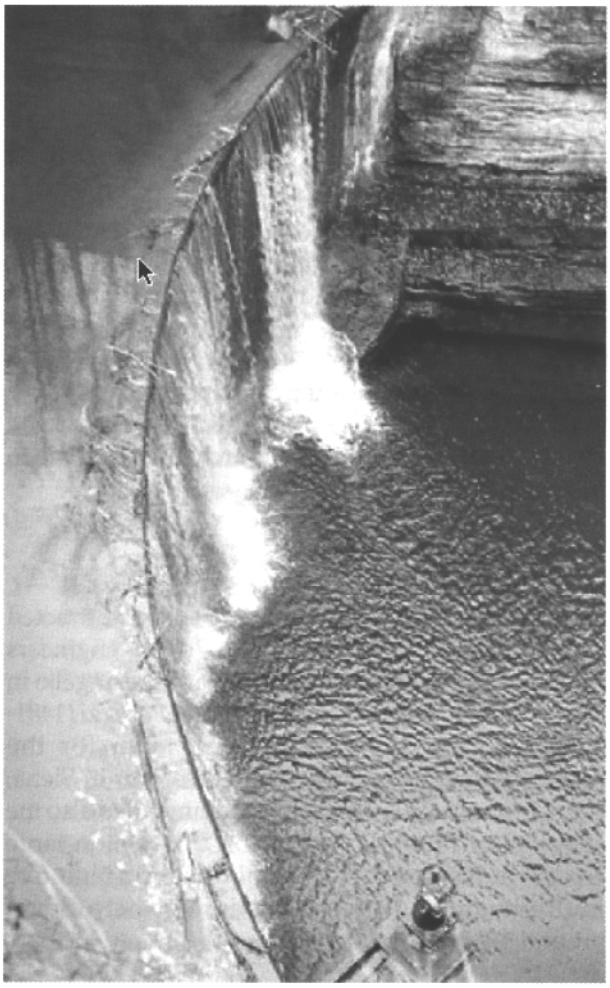


Figure 10: Ithaca dam (New York, USA), photograph taken in 1998 (Courtesy of Mr G. Toombes)

was built of concrete instead of masonry".[35] Australian mass concrete dams were often built utilising stones set in concrete, a technique called plum concrete or cyclopean concrete. "Plum stones to the maximum size that can be handled by two men" were used.[36] "All the concrete [was] mixed by hand [and] wheeled into place in barrows and trucks".[36] The concrete was laid in 3 feet courses "held between mould-boards [formwork] 10 ft long by 3 ft 6 in. high".[36] By comparison, stone masonry necessitated a skilled workforce (ie. stonemason artisans) and a plant to carry stones. For example, a machinery capable of carrying 2 to 6 tons was used to handle and place the masonry blocks at Parramatta dam.[30] The relative ease of concrete construction contributed to the lower cost but also suited well new colonies without skilled manpower.

A third advantage of concrete construction was the flexibility of shape. "With concrete [...] labour is saved and concrete has the farther advantage that it can be rammed into any irregular cavity".[37] Concrete offered a flexibility of shapes and curved designs (eg. cupola shape). The introduction of concrete as a construction material paved the way for the newer modern designs: constant-angle and cupola arch dams: eg. Ithaca (1903), figure 10.

Remarks

The development of concrete dam construction under the leadership of Dobson and Darley in the 1870s to 1900s marked the end of large stone masonry dam construction in Australia. From 1890, the highest large dam in Australia had been a concrete structure until the late 1950s.[38]

An interesting parallel is the construction of masonry arch bridges. O'Connor[39] showed that the construction of (notable) stone arch bridges came to an end basically in 1909.[9]

Multiple arch dam design

The development of multiple arch dams attracted some interest in Spain and Italy. Roman engineers built the oldest multiple-arch dam at Esparrageljo in Spain.[2] In 1530 the architect Baldassare Peruzzi (1481-1536) proposed a multiple arch dam for the reconstruction of a fishing pond reservoir in Siena, Italy. Turriano (1511-1585)[10] recommended also the selection of multiple arch dams "for use on large rivers" in his Codex.[40] Villareal de Berriz built five multiple arch-buttress dams in Northern Spain around 1730.

In the 19th century two significant structures were Meer Allum and Junction Reefs. Although Junction Reefs dam was smaller than Meer Allum, it incorporated new advanced features: elliptical arches, and a sloping upstream face which enhances the dam stability. Further advances in design were made with the Hume Lake and Coolidge dams in the USA.

7 SUMMARY AND CONCLUSION

The historical development of arch dams may be summarised in five stages (table 1). The world's oldest arch dams were built by the Romans in France and Spain. They were followed by the Mongols who built arch dams in Iran during the 13th and 14th centuries. However it is not until the 19th century that significant progress in arch dam design was made. Four remarkable structures were the Meer Allum dam (India 1804), the Jones Falls dam (Canada 1831), the Zola dam (France 1854) and Parramatta dam (Australia 1856). All four of them are still in use today and demonstrate the soundness of arch dam design.

Australian engineers pioneered the use of concrete as a construction material for arch dams. The world's oldest concrete arch dam was completed in Queensland in 1880: the 75-Miles thick arch dam near Warwick. The world's oldest concrete thin-arch dam was the Lithgow No. 1 dam in New South Wales (1896). Both the 75-Miles and Lithgow No. 1 dams were made of non-reinforced concrete.

Modern arch dam designs were further developed in North-America. The world's oldest cupola dam was completed in 1903 at Ithaca (USA).[25] The first constant-angle arch dam was completed in 1914. Modern multiple arch designs were completed in 1908 (Hume Lake) and 1928 (Coolidge). Since then, no major breakthrough has taken place. It is the writers' opinion that the introduction of concrete as a construction material heralded a major innovation in arch dam shape.

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REFERENCES

1. Smith N. A history of dams. The Chaucer Press, Peter Davies, London, UK, 1971.

2. Schnitter NJ. A history of dams: the useful pyramids. Balkema Publ., Rotterdam, The Netherlands.1994.

3. Schnitter NJ. The evolution of the arch dam. Intl Water Power & Dam Construction, 1976;28, Oct:34-40 & Nov:19-21.

4. Pelletreau A. Barrages cintrés en forme de voûte. (Curved dams with arch design.) Annales des Ponts et Chaussees, 1er semestre, 1987:198-218 (in French).

5. Jorgensen LR. The constant-angle arch dam. Transactions, ASCE, 1915;LXXVIII:685-721. Discussion: LXXVIII:722-733.

6. Benoit F. Le barrage et l'aqueduc Romains de Saint-Rémy de Provence. (The Roman dam and aqueduct of Saint-Rémy de Provence.) Revue des Etudes Anciennes,1935:332-340 (in French).

7. Goblot H. Sur quelques barrages anciens et la genèse des barrages-voûtes. (On some ancient dams and the genesis of the arch dams.) Revue d'Histoire des Sciences,1967;XX(2)April-June:09-140 (in French).

8. Agusta-Boularot S, Paillet JL. Le barrage et l'aqueduc occidental de Glanum: le premier barrage-voûte de l'histoire des techniques?" (The dam and western aqueduct of Glanum: the first arch-dam in the history of techniques?) Revue Archéologique, 1997(1): 27-78 (in French).

9. Saladin H. (1886). Rapport sur la mission faite en Tunisie de Novembre 1882 à Avril 1883." Archives des Missions Scientifiques et Littéraires, Ministère de l'Instruction Publique, France, 1886;Serties 2, Vol.13:1-225 (in French).

10. O'Connor C. Roman bridges. CUP, Cambridge, UK,1993.

11. Schnitter N. Les barrages Romains. (The Roman dams.) Dossiers de l'Archéologie, Séries Les Aqueducs Romains, 1979;38,Oct.-Nov:20-25 (in French).

12. Stark H von. Geologische und technisiche beobachtungten an alten antolischen Taslsperren. (Geological and technical construction details of anicient dams in anatolia). Die Wassersirtschaft, 1957-58:16-19. (in German).

13. Goblot, H. Kébar en Iran sans doute le plus ancien des barrages-voûtes: l'an 1300 Environ. (Kebar in Iran possibly the oldest arch dam: around 1300 AD) Arts et Manufactures, 1965;154:43-49.

14. Goblot, H. Du nouveau sur les barrages Iraniens de l'epoque Mongole (Some news on the Mongolian dams in Iran.) Art et Manufactures, 1973;239:14-26 (in French).

15. Fevrier PA. L'armée Romaine et la construction des aqueducs. (The Roman army and the construction of aqueducts.) Dossiers de l'Archéologie, Séries Les Aqueducs Romains, 1979;38,Oct./Nov:88-93 (in French).

16. Leveau P. Research on Roman aqueducts in the past ten years. Future Currents in Aqueduct Studies, Leeds, UK, T. Hodge ed, 1991:149-162.

17. Legget RF. The Jones Falls dam on the Rideau Canal, Ontario, Canada. Trans. Newcomen Society,1957-9;31:205-215. Discussion: Vol.31: 215-218.

18. Coyne A. Les barrages. Différents types et mode de construction. (Dams. Different types and construction technique.) Le Génie Civil 1880-1930, 50th Anniversary Issue,1930; November:202-205 (in French).

19. Coyne A. Arch dams: their philosophy. Jl of Power Division, ASCE, 1956;82(PO2):959/1-32.

20. Ash, R, Heinrichs P. Parramatta single arch dam - from 1856 and still going strong. Proc. 1st Intl and 8th Australian Engineering Heritage Conf, Newcastle, Australia, 29 Sept.-2 Oct.1996:9-19.

21. Wade LAB. Concrete and masonry dam-construction in NSW. Min. of Proc. of Instn. of Civil Engineers, London, 1909;178(9)Paper 3791:1-26. Discussion: Vol. 178, (9):27-110.

22. Chanson H, James P. Rapid reservoir sedimentation of four historic thin arch dams in Australia. J. Performance of Constructed Facilities, ASCE, 1998a;2(2)May:85-92. Errata: 12, (3):69.

23. Engineering Record . An unusual arched dam. The Engineering Record, 1903;47(2):56.

24. Schuyler JD. Reservoirs for irrigation, water-power and domestic water supply. John Wiley & Sons, 2nd edition, New York, USA.1909.

25. Chanson H, and James DP. Historical development of arch dams in Australia: from advanced designs to engineering failures. Research Report CE 157, Dept. of Civil Engineering, The University of Queensland, Brisbane, Australia, August ,1998b.ISBN 1 86499 0791.

26. Chanson H. The 75-Miles dam in Warwick: the world's oldest concrete arch dam.Royal Historical Society of Queensland Journal, 1999;17(2)65-75.

27. Lewis M. (1988). Two hundred years of concrete in Australia. Concrete Institute of Australia, Sydney, Australia, 1988.

28. Harper BSC. Edward Dobson and the mass concrete on Stony Creek for the Geelong water supply. Proc. 9th Nat. Conf. on Engineering Heritage, IEAust., Ballarat VIC, Australia, 1998,15-18 March:97-106.

29. Schulze O. Notes on the Belubula Dam. Trans. Australian Institute of Mining Eng, 1897;4, Paper 52:160-172 (+ 2 plates).

30. Wegmann E. The design and construction of dams. John Wiley & Sons, New York, USA, 7th edition.1922.

31. Binnie GM. Masonry and concrete dams 1880-1941. Industrial Archaeology Review, 1987;X(1):41-58.

32. Burgh EM de. Some notes on the construction of curved dams in New South Wales. Concrete and Constructional Engineering, 1917;12(2):83-90.

33. Wegmann E. The design and construction of masonry dams. John Wiley & Sons, New York, USA, 3rd edition.1893.

34. Creager WP. Engineering of masonry dams. John Wiley & Sons, New York, USA.1917.

35. Gordon G. Concrete dam for Geelong water works. Roorkee Professional Papers on Indian Engineering, Second Series, 1875;4:402(&2 plates).

36. Darley CW. Curved concrete walls for storage reservoirs. Proc. Royal Soc. of New South Wales, Australia, ,19 Dec.1900;34: xlix-lxii.

37. Dobson E. The Geelong water supply, victoria, Austrlia. Min of Proc. Int of civil Engrs. London. 1879;56:94-127 & plate.

38. Nimmo WHR. Historical review of dams in Australia. ANCOLD Bulletin, 1966;(18):11-51.

39. O'Connor C. The design of bridges: a historical study. Inaugural lecture, University of Queensland, Australia. 13, June 1974.1974.

40. Garcia-Diego JA. The chapter on weirs in the Codex of Juanelo Turriano. Technology and Culture,1976:217-234.

41. Imperial Gazetteer of India, 1907-31, Clarendon Press, UK, 1908;13:311.

42. Mill J. (1848). The history of British India. J. Madden, London, UK, 5ed.10 vols.1848;7:21 & 25.

43. Teignmouth HS Baron. The private record of an Indian governor-generalship: the correspondence of Sir John Shore, Governor-General, with Henry Dundas, president of the Board of Control 1793-1798. Harvard University Press, Cambridge.

44. Coltheart L. Fraser, D. Landmarks in public works. Engineers and their works in New South Wales 1884-1914. Hale & Iremonger Publ., Sydney, Australia,1987.

45. Newland JT. (1994). The Goondah-Burrinjuck railway. Australian Railway Historical Society, Star Printery, Erskineville NSW, Australia, 1994.

46. Burgh EM de. The practical work of starting a great engineering entreprise. Meeting at Sydney University Engineering Society, Australia, 1908, 8 July. (Also in "Landmarks in Public Works. Engineers and their Works in New South Wales 1884-1914.", L. Coltheart and D. Fraser eds, Hale & Iremonger Publ., Sydney, Australia, 1987:130-138.)

47. Delocre M. Mémoire sur la forme du profil à adopter pour les grands darrages en maçonnerie des réservoirs. (Memoir on the shape of the profile to adopt for large masonry dams.) Mémoires et Documents, Annales des Ponts et Chaussées, Paris, France, 1866;2nd Sem.:212-272 (in French).

48. Rankine WJM. Report on the design and construction of masonry dams. The Engineer, Jan. 5,1872;33:1-2.

49. Legget RF. Rideau Waterway. University of Toronto Press, Toronto, Canada, Revised ed. 1972.

50. Whitmore RL. Eminent Queensland Engineers. Institution of Engineers, Australia, Queensland Division, Consolidated Printers, Brisbane.1984.

51. Report of the Queensland Railway Commissioner, 1878.

52. Brown F. Zola. A Life. MacMillan, London, UK.1996.

53. Brown JM. Sir Proby Cautley (1802-1871), a pioneer of Indian irrigation. History of Technology, 1978;3:35-89.

54. Hager WH. Sir Proby Cautley (1802 bis 1871), ein Pionier des Bewässerungskanalbaus. Die Wasserwirtschaft, 1993;83(12):676-678 (in German)

55. Buckley RB. The irrigation works in India. E.&F.N. Spon, London, UK,2nd ed.1905.

BIBLIOGRAPHY

Chanson H. (1997). A short history of stepped cascades in Australia. ANCOLD Bulletin, 1997;Aug(106):01-111.

Darley CW. Concrete and masonry dam-construction in New South Wales. Discussion. Min. of Proc. of Instn. of Civil Engineers, London, 1909;178,(9):27-28 & 47-49.

Sankey RE. Report on the Coliban and Geelong water schemes of water supply. Report, presented to both Houses of Parliament, Victoria (Australia), 11 Nov, 1871.